

PITCH ANGLE DISTRIBUTIONS OF 35-1000 keV PROTONS
AT QUASI-PERPENDICULAR INTERPLANETARY SHOCKS

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ABSTRACT

The characteristic features of the scatter-free acceleration process near perpendicular shocks are examined in the upstream and downstream pitch angle distributions of 35-1000 keV protons. Reasonable quantitative agreement is found between theoretical predictions and observations. The role played by "bottle" geometries, leading to enhanced acceleration, is highlighted.

1. Introduction. The mechanisms responsible for particle events associated with the passage of interplanetary shock waves have received much experimental and theoretical attention (Axford, 1981; Sanderson et al., 1985). In particular, the relative importance of scatter-free and diffusive acceleration models has been subjected to close scrutiny, much of the recent evidence coming from the observations made by the low energy charged particle experiment on the ISEE-3 (now ICE) spacecraft in orbit around the Lagrange point L1 during the period 1978-80. In this paper we examine the behaviour of the pitch angle distributions of 35-1000 keV protons associated with five interplanetary shocks which exhibited some of the most characteristic features of the scatter-free (gradient drift) acceleration model, as discussed by Sanderson et al. (1985).

Shock spikes, sharp increases in the intensity of low energy ions in close proximity to the passage of quasi-perpendicular interplanetary shocks, are normally attributed to particles accelerated in a single interaction with the shock wave, during which they drift along the electric field due to the motion of the shock in the frame of the plasma. Numerous, increasingly refined numerical simulations and analytical calculations have clarified many features of the process (see Decker, 1983). The behaviour of the anisotropy, in terms of spherical harmonics, was examined by Sanderson et al. (1985).

Observations presented in this paper were obtained with the low energy proton experiment onboard the ISEE-3 spacecraft (Balogh et al., 1978), which provides a 180-point measurement of the distribution function of 35-1000 keV protons every 16 seconds. The technique for describing the distribution function in terms of pitch angle distribution in the frame of the solar wind was worked out by Erdős (1981).

Time-reversed trajectory calculations for various shock parameters have been used to derive the qualitative features of the pitch angle distribution upstream and downstream of the shock. In Figure 1, results are shown for a shock of velocity $w_s = 200$ km/s, with an angle $\alpha = 80^\circ$ between the shock normal and the upstream magnetic field, and therefore a transformation velocity into the electric field free frame (e.g. Axford, 1981) $w = w_s \sec \alpha \approx 1100$ km/s. We assumed a particle velocity $v = 3000$ km/s and an exponent of the differential power law spectrum $\gamma = 2.5$.

Peak intensities (in the solar wind frame) can be derived from adiabatic theory. The critical pitch angle for reflection upstream of the shock in the E-free frame is $\mu_c = \sqrt{1 - B_u/B_d}$, where B_u and B_d are the magnetic field strengths upstream and downstream of the shock, respectively. The transformation into the solar wind frame gives

$$\mu_u = \frac{\mu_c + w/v}{\sqrt{1 + 2\mu_c w/v + (w/v)^2}} \quad (1) \quad \text{and} \quad \mu_d = \frac{w/v}{\sqrt{1 + (w/v)^2}} \quad (2)$$

as the cosine of the pitch angle for which the maximum occurs in the distributions, respectively upstream and downstream of the shock. We note that the maxima in the distributions occur at pitch angles which depend on particle velocity. For oblique shocks and low energy particles the downstream distributions do not peak exactly at 90° , although as the particle energy increases, the peak of the distribution for given shock velocity and geometry moves to 90° , or $\mu = 0$.

For simple shock geometries, the gradient drift model predicts a sharp peak in the upstream pitch angle distribution at a value of μ given by (1) and the existence of a loss cone due to particles transmitted through the shock.

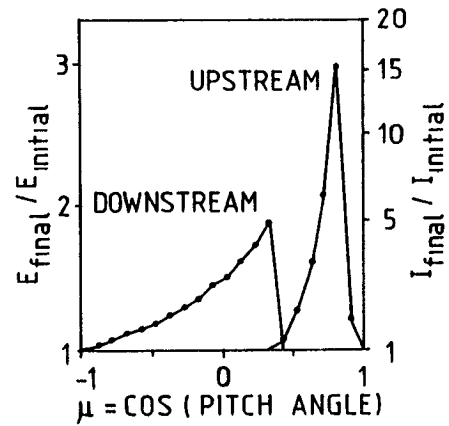


Fig. 1. Time-reversed calculation of upstream and downstream pitch angle distributions.

2. Observations. Pitch angle distributions upstream and downstream of five shock associated events are shown respectively in Figures 2 and 3. The energy dependence of upstream distributions is illustrated qualitatively in Figure 2, where pitch angle distributions are shown from two energy channels (35-56 keV and 91-147 keV, respectively).

The transformation velocity w can be estimated, using (2), from the position of the peak in the downstream pitch angle distributions, and compared to the value calculated from w_s and α as determined by Sanderson et al. (1985). The two sets of values, $w(\text{peak})$ and $w(w_s, \alpha)$ respectively, are shown in Figure 3.

The shift in the peak of the pitch angle distribution towards $\mu = 0$ for increasing energies was clearly identifiable on 26.7.79 and

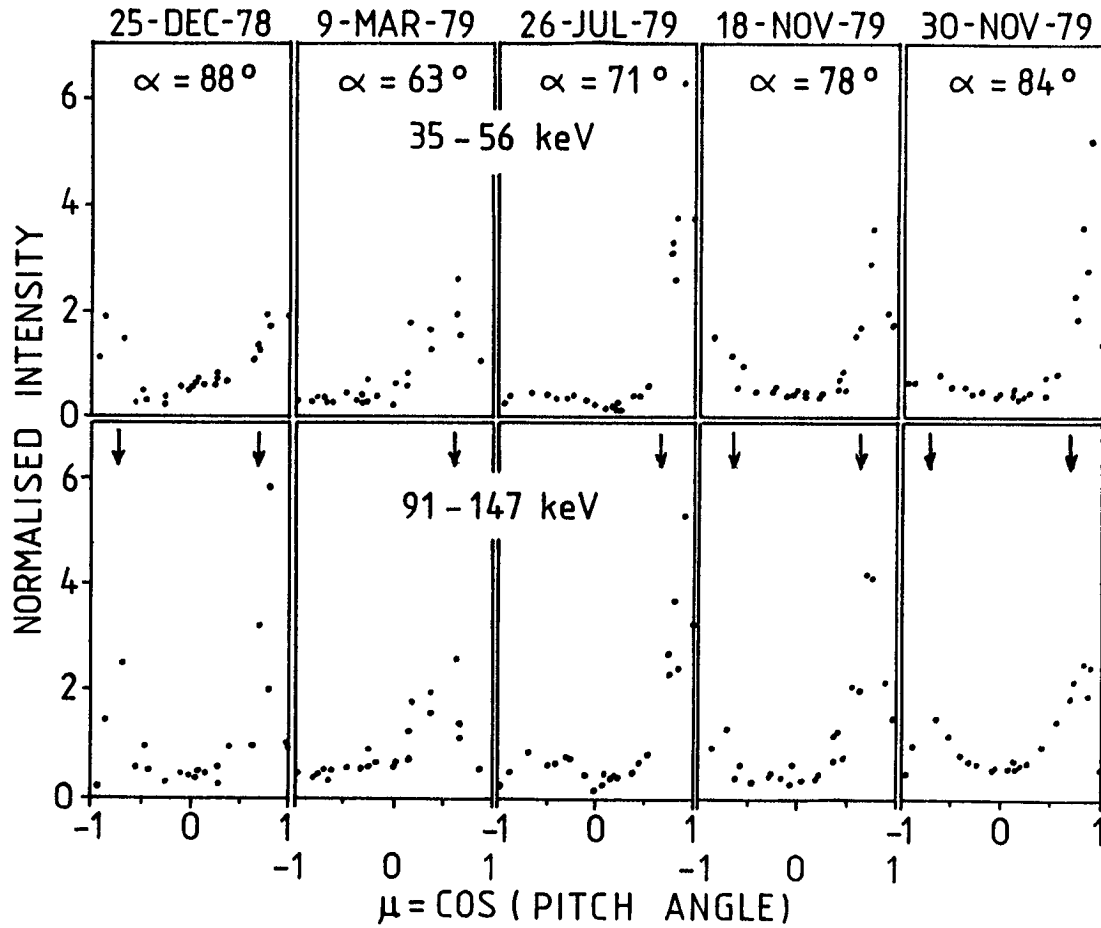


Fig. 2. Upstream pitch angle distributions in five shock-spike events. The arrows indicate the calculated values of μ_c .

μ_d	0.53	0.04	0.81	?	0.68
$w(\text{peak})$	1800	100	4000	?	2700 km/s
$w(w_s, \alpha)$	3800	370	330	700	900 km/s

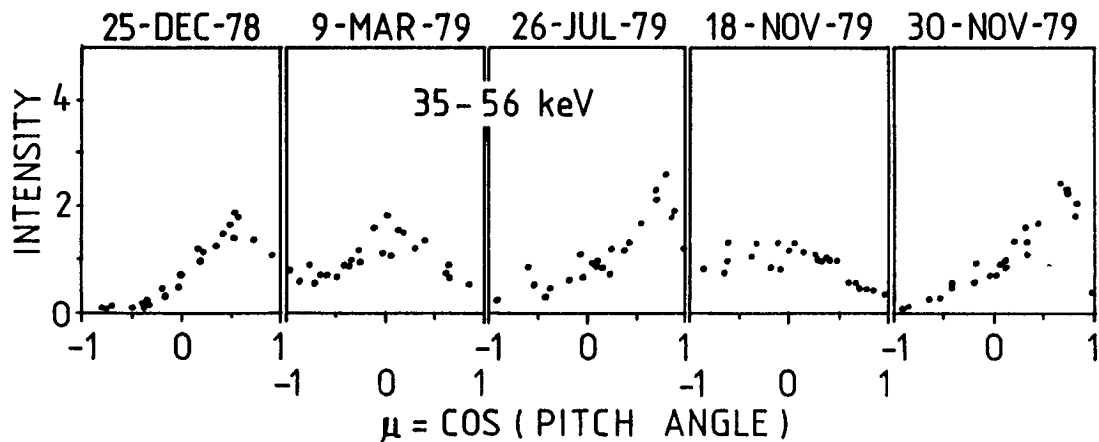


Fig. 3. Downstream pitch angle distributions.

30.11.79, illustrated in Figure 4 for the second of these events. On 9.3.79 and 18.11.79 the peak of the distribution was at $\mu = 0$ for all energies. On 25.12.78, the behaviour of the peak could not be ascertained due to poor statistics at high energies.

3. Discussion and Conclusions. For particles reflected upstream of the shock we observe a sharp cut-off in the pitch angle distribution, characteristic of a loss-cone in the distributions even at the lowest (~ 35 keV) energies, corresponding to $v \approx 3000$ km/s. The existence of upstream reflected particles implies that the transformation velocity is in all cases less than about 3000 km/s.

The existence of a bi-directional loss cone as shown in Figure 2 at higher energies in at least two, possibly three events (25.12.78, 30.11.79, possibly 18.11.79), corresponding to the largest values of α , appears to indicate that the upstream magnetic field lines intersected the shock in such a way as to form a short-lived magnetic "bottle" as discussed by Balogh and Erdős (1983).

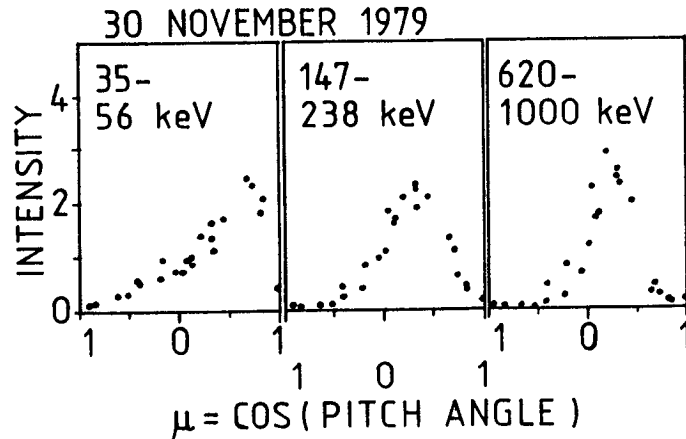


Fig. 4. Energy dependence of the downstream pitch angle distribution.

The effective shock velocity, determined from the position of the peak in the downstream pitch angle distribution, is different from that determined using w_s and the time-averaged value of the angle $\langle \alpha \rangle$ between the upstream magnetic field and the shock normal. This can be explained by either a small error (a few degrees) in the determination of the shock normal, or possibly by the sensitivity of pitch angle distribution to $w_s \langle \sec \alpha \rangle$ whereas the calculated velocity is $w_s \sec \langle \alpha \rangle$.

Overall, the shape and energy dependence of pitch angle distributions support the identification of these five events as examples of the gradient-drift acceleration process. However, the model should include the effect of fluctuations in the angle between the shock normal and the upstream field. Furthermore, at close-to-perpendicular shocks, the special geometry identified as a possibly short-lived magnetic "bottle" (as proposed by Balogh and Erdős, 1983) is likely to contribute significantly to the intensity of the shock spike.

References

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